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14. ABSTRACT

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Long-Term Solar Variability: Evolutionary Time Scales

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1. INTRODUCTION

Galileo, who played a central role in the modern discovery of sunspots, may have wondered whether the Sun varies. Certainly, his 17th century contemporaries did. The Sun itself all but answered this question a few decades later when it nearly stopped forming sunspots as it entered what is now known as the Maunder Minimum. Herschel's speculation that the price of wheat might be related to the number of sunspots indicates that the possibility of solar variability was firmly established in the scientific thought of the late 18th century [*Eddy*, 1983]. In the mid-19th century, the ~11-yr variation in sunspot number was recognized, apparently first by Schwabe. Indeed, it sometimes seems even today that solar variability is all but defined as this variation in sunspot number. One of the first efforts to get beyond counting sunspots was Abbot's determined program of ground-based solar radiometry in the early years of the 20th century [e.g., *Abbot*, 1934], which foundered mainly on the difficulty of correcting accurately for atmospheric extinction. Successful detection of the solar cycle in the Sun's radiative outputs did come, however, when measurements of 10.7 cm radio flux variations in the mid-20th century opened what might be called the modern era in the study of solar variability.

The final decades of the 20th century brought remarkable advances in our knowledge of solar variability. In 1974, observations to follow the cyclic variation of chromospheric Ca II K-line emission were begun at the National Solar Observatory [*White et al.*, 1998]. Eddy's studies of historical records of solar activity stimulated renewed interest in solar variability and its possible effect on terrestrial climate [*Eddy*, 1976]. Measurements from space, however, took center stage. Starting in 1978, variations in solar total irradiance were detected and monitored by a series of spacecraft, among which the ACRIM experiment aboard the Solar Maximum Mission (SMM) satellite produced a pivotal series of measurements between 1980 and 1989 [*Willson*, 1997]. Theory closely followed measurement, and by the close of the century a picture of solar radiative variability on time scales ranging from days to years had emerged.

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2. SOLAR MAGNETIC ACTIVITY AND VARIABILITY

The solar atmosphere harbors a broad range of non-thermal phenomena collectively called activity. On the global scale, this activity is responsible for the sharp temperature increase above the solar photosphere. On the local scale it produces a variety of discrete features, including the dark sunspots and bright faculae of the photosphere, the emission plages and network of the chromosphere, and the intricate structures of the solar corona.

The solar atmosphere is permeated by magnetic fields. It is generally accepted that much (though perhaps not all) of what we call solar activity arises from the generation, evolution, and annihilation of these magnetic fields. The most prominent magnetic structures on the solar surface are the active regions, with their spots, faculae, and overlying chromospheric plages. Active regions erupt and decay with lifetimes of a few months. As an active region ages, its spots disappear. Its faculae disperse, merge with the surrounding network, and gradually also disappear. Large sunspots can live for several weeks, a time scale which accidentally corresponds to the ~25 day solar rotation period. The faculae of an active region may persist, at least collectively, for a few months. The Sun characteristically shows longitudinal asymmetries in the distribution of its active regions, which it maintains by its tendency to create successive active regions in relatively fixed locations. These activity complexes can last for many months or even years—much longer than the lifetime of individual active regions.

Many aspects of solar activity are accompanied by temporal variability; indeed, the very word "activity" strongly suggests variation. Solar irradiance variability is widely, but not universally, attributed to flux deficits produced by dark sunspots, and excess flux produced by bright faculae in both active regions and the network [e.g., *Foukal and Lean*, 1988; *Lean et al.*, 1998]. Dissenters argue that part of the variability, at least on the cycle time scale, arises from a non-facular and possibly global component, perhaps small changes in the surface temperature [e. g., *Kuhn and Libbrecht*, 1991; *Li and Sofia*, 2001]. All substantially agree, however, that sunspots and faculae cause solar irradiance fluctuations amounting to 0.1% or so on time scales of days to weeks, with sunspots producing the most obvious effects. These variations arise both from the emergence and decay of individual solar active regions, and from solar rotation that carries the active regions into and out of view on the solar disk. The relative prominence of the sunspot signature in the initial SMM/ACRIM radiometry helped create a widespread (but mistaken) expectation that the Sun would become brighter as its 11-yr activity cycle waned and sunspots grew scarce [see, e.g., *Eddy*, 1983]. In fact, sustained measurements showed that the Sun's brightness varies directly with the rise and fall of the activity cycle (Figure 1). In terms of the spot/facular model, this implies that solar irradiance variability on the 11-year activity cycle time scale (unlike shorter time scales) is dominated by excess radiation from faculae and bright magnetic network features, rather than the sunspot deficit. The dissenters enter here.

Our understanding of solar variability on time scales longer than the 11-yr activity cycle remains considerably more sketchy. Studies of radioisotopes such as ^{14}C and ^{10}Be provide valuable, albeit indirect, insight about solar variability on time scales of centuries to millennia [e.g., *Beer*, 2000]. On even longer (i.e., evolutionary) time scales, contemporary solar observations, paleoclimatic studies, and analyses of lunar and meteoritic samples offer only teasing hints. Fortunately, the behavior of stars similar to the Sun offers a powerful approach for exploring the likely past history, present state, and future course of solar variability.

This chapter considers solar and stellar brightness variations, primarily on the time scale of years, and the evolution of these variations during the main-sequence lifetime of a star like the Sun. Only variability arising from magnetic activity is considered. Neither transient effects caused by flare-like events nor the long-term secular luminosity increase associated with interior evolution will be further noted. Before proceeding, however, we should perhaps remind ourselves how pervasively the Sun influences our thinking and expectations. The Sun provides our vocabulary: spots, faculae, plages, active regions, chromospheres, coronae—such terms have all been borrowed from solar astronomy, and underlie the conceptual framework used to interpret a wide range of stellar observations. The Sun also suggests possible mechanisms for variability, such as rotational modulation, active region evolution, and activity cycles. We must beware, lest familiarity with the Sun lure us into traps of circular reasoning.

3. STELLAR PROXIES FOR THE SUN

3.1. Physical Determinants of Stellar Activity and Variability

Contemporary astrophysics has accumulated considerable evidence indicating that magnetic activity following a predictable evolution is a normal feature of lower main-sequence stars, including the Sun. Furthermore, the magnetic

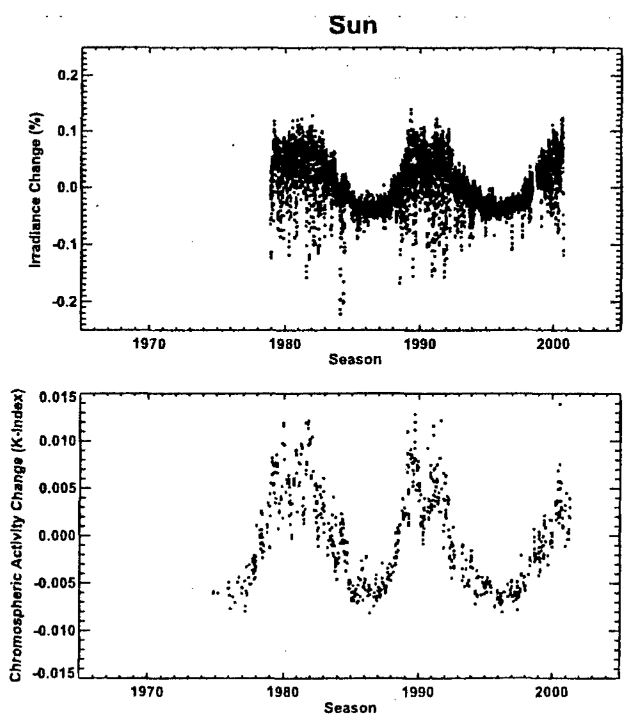


Figure 1. Solar variability. Upper panel: solar radiometry (1978-present) from spaceborne radiometers (courtesy C. Fröhlich); Lower panel: solar Ca II K-line spectroscopy (1974-present) from NSO/KP (courtesy W. Livingston).

activity of such stars is apparently governed primarily by rotation and mass. In one important sense, mass is absolutely decisive: only stars with convective envelopes appear to harbor magnetic activity. Beyond this, rotation seems to be the more dominant determinant. Both observations and theory argue that the surface rotation rate of a lower main-sequence star quickly loses its memory of initial conditions, after which it gradually slows in a manner that depends primarily on stellar age. Accordingly, for a specific star such as the Sun, the evolution of its magnetic activity and variability is very much the story of its rotation.

3.2. *The Influence of Rotation on Stellar Magnetic Activity*

Although it was first proposed over eighty years ago that the surface magnetic fields of the Sun are produced by dynamo action [*Larmor,* 1919], our understanding of the solar dynamo remains annoyingly incomplete. Theory suggests that the dynamo is seated near the base of the Sun's convective envelope. The key ingredients of the dynamo are rotation and convection, which interact to produce both differential rotation and helicity. Differential rotation readily converts poloidal magnetic flux into toroidal flux and amplifies it, while helicity twists toroidal flux, thereby regenerating poloidal field. Something resembling this oscillatory, self-sustaining process is generally believed to underlie the 11-yr solar activity cycle [e.g., *Weiss,* 1994].

Dynamo theory predicts that magnetic-field amplification should depend strongly and directly on stellar rotation rate, and observations agree that rapidly rotating stars show relatively more vigorous magnetic activity. Thus, the existence of a causal relation between rotation and the magnetic activity of lower main-sequence stars is widely accepted. In practice, the rotation-activity relation is indirectly expressed in terms of chromospheric or coronal emission rather than magnetic flux or field strength, because direct measurements of stellar magnetic fields are difficult and therefore scarce. Strictly speaking, commonly observed activity indicators, such as chromospheric Ca II H + K line-core emission or coronal soft X-ray emission, prove only that a star's outer atmosphere is being heated by non-thermal processes. Solar studies, however, have demonstrated that regions of enhanced chromospheric and coronal emission coincide with underlying concentrations of photospheric magnetic flux, and that emission strength scales directly with mean field flux in these regions [*Skumanich, Smyth and Frazier,* 1975; *Schrijver et al.*, 1989]. Although temperature, surface gravity, and chemical composition probably all affect the complex and incompletely understood connection between surface magnetic flux and its radiative indicators, these indicators are, nevertheless, widely accepted as reliable diagnostics of stellar magnetic activity.

On both theoretical and experimental grounds, it seems likely that the basic convective pattern in the outer envelope of a lower main-sequence star changes, as its rotation rate decreases, from something unlike anything observed on the solar surface, namely, a regular distribution of elongated rolls aligned parallel to the stellar rotation axis, to a more irregular, cellular pattern at least vaguely reminiscent of solar granulation and other modes of solar convection. Recent work suggests that this transition is both more complicated and less abrupt than once thought [*Miesch,* 2000], but opinion still appears to agree that the transition does occur. Such a dramatic change must surely affect the behavior of the highly nonlinear stellar dynamo. Thus, there is reason to suspect that the magnetic activity and the attendant brightness variability of young, rapidly rotating stars may not be simply more vigorous versions of what is observed on the Sun. Indeed, young stars tend to show strong, non-cyclic activity with relatively complicated temporal behavior, quite unlike what we see on the present-day Sun. These differences will be described in more detail subsequently.

Early investigations of stellar activity tended to focus on its relation to stellar age, rather than rotation. In fact, both mean activity and surface rotation rate decline with age in nearly identical ways among lower main-sequence stars. The classic Skumanich power-law dependence (Ca II H+K emission and rotation rate are both proportional to the inverse square root of stellar age for stars of similar mass: [*Skumanich,* 1972]) remains a simple and useful rule for lower main-sequence stars throughout much of the age range considered here, despite the fact that it fails for very young stars as well as for certain active binaries. Therefore, it seems natural to ask whether stellar activity is more fundamentally linked to rotation rate or age. The clearest answer comes from a class of interacting binary stars, the RS CVn systems. These systems contain aging, evolved stars that have maintained rapid rotation through tidal coupling with their nearby companions. They also exhibit very high levels of activity, proving thereby that the causal determinant for stellar activity is rotation, rather than age.

Whereas the magnetic activity and variability of ordinary lower main-sequence stars depend strongly on rotation, rotation itself is governed by age and mass. For a star with a convective envelope, an inescapable fact of life is that its rotation will slow as its magnetically coupled wind carries away angular momentum [*Schatzman,* 1962]. This magnetic braking is strongly dependent on rotation rate, so the deceleration is, initially, very rapid. Theory suggests that the rotational velocity of a solar mass star becomes independent (to a few percent) of initial angular momentum within a few hundred Myr [*Kawaler,* 1988]. Measured rotation periods for G-type stars some 700 Myr old in the Hyades and Coma Berenices clusters, which show little scatter at any given color, support this conclusion.

The past 20 years have witnessed remarkable progress in our empirical and theoretical understanding of the angular momentum evolution of young solar-type stars [e.g., *Krishnamurthi et al.,* 1997]. A number of factors involving both the structure of the star as well as its interaction with its environment enter the story. As a star settles onto the main sequence, the formation of a dense, radiative core decreases its moment of inertia, which tends to spin it up, while interactions with remnants of the stellar accretion disk oppose this tendency. To complicate matters further, the mechanism for angular momentum loss apparently saturates above some critical rotation rate, which hampers the efficacy of magnetic braking. The growing radiative core also decouples to some degree from its surrounding convective envelope, which further alters the accounting. Depending on its specific initial conditions, an infant sunlike star may settle down more-or-less directly onto the main sequence, with a rotation period of a few days, or it may undergo a more dramatic spin-up, spin-down episode which, nevertheless, leads the star to almost the same rotational state after 100 Myr or so. Which path the young Sun took is probably unknowable but, in any case, left no strong mark on its subsequent evolution.

The surface rotation rate of F- to K-type main-sequence stars several hundred Myr old shows some dependence on stellar mass, declining from ~7 km/sec to ~ 4 km/sec as mass decreases by 30% or so [*Radick et al.,* 1987]. This trend in mean rotation rate is probably a relic of early evolution, because the temporal evolution of rotation for such stars does not appear to be strongly mass dependent after an age of a few hundred Myr.

3.3. The Influence of Mass on Stellar Magnetic Activity

Stellar mass should also affect magnetic activity. As mentioned above, mass is absolutely decisive in one important sense: stars more than about 50% more massive than the Sun (i.e., earlier than mid F-type), which lack deep convective envelopes, do not experience activity cycles (or, for that matter, pronounced rotational slowdown). It should be noted, however, that early F-type stars do show evidence of magnetic activity [e.g., *Giampapa and Rosner,* 1984]—what is absent, apparently, are the large active regions so characteristic of solar magnetic activity. On theoretical grounds, mass should also strongly affect the behavior of the stellar dynamo. Specifically, the dynamo number, which parameterizes the efficiency of the hydromagnetic dynamo in mean field theory, depends as strongly on the time scale for convective turnover at the base of the stellar envelope as it does on rotation rate [*Durney and Latour,* 1978]. This time scale in turn depends strongly on stellar mass, increasing monotonically with decreasing mass among lower main-sequence stars, and rising especially steeply between mid F- and mid G-type main-sequence stars [*Gilliland,* 1985]. Thus, lower-mass stars should be relatively more active, among otherwise comparable stars. Empirically, this seems to be the case: K-type stars in the Hyades, for example, tend to show more evident activity than do F-type stars, and G-type stars tend to be in the middle, but more closely resemble the K-type stars [*Radick et al.,* 1987].

3.4. Other Factors Affecting Stellar Magnetic Activity: Composition and Companions

Like stellar mass, chemical composition strongly affects convective zone structure, and should therefore influence magnetic activity. The identification and measurement of the real and apparent effects of composition on stellar magnetic activity, however, remains largely an unfinished task, in part because the nearby stars seem to be fairly homogeneous in composition, in part because it is difficult to separate composition effects from other factors.

In brief, a metal-rich star will have a deeper convective zone and a longer convective turnover time scale than a metal-poor star of the same mass. In this respect, metal enhancement mimics lower mass, and a metal-rich star should be relatively more active than its metal-poor counterpart of equal mass. In practice, it is difficult to test this hypothesis, because it is not easy to identify stars of strictly equal mass. Furthermore, stellar masses are often estimated from intermediaries, such as photometric color indices, that are sensitive to metallicity, so it is difficult to avoid circularity.

Even if chemical composition had no intrinsic effect on stellar magnetic activity, it would enhance the apparent activity of metal-rich stars through its influence on radiative activity diagnostics such as chromospheric Ca II H+K emission. Calculations suggest that Ca II H+K emission depends strongly and directly on metallicity. The Mount Wilson S-index, which measures the ratio of the combined fluxes in two 1-A continuum windows centered on the H and K lines to the sum of the fluxes in two 20-A continuum windows on either side of the doublet, could be even more sensitive because of enhanced line-blanketing effects outside the cores of the lines.

Several decades ago, starspots were invoked to explain the photometric variability of the RS CVn binaries. Their extreme activity (relative to the Sun) and the ability of tidal coupling to enforce rapid rotation indicates that the presence of a close, interacting companion can dramatically affect the rotational evolution and therefore the magnetic activity of a star.

4. WHAT MAKES A SUNLIKE STAR?

The Sun appears to be a rather ordinary star, a conclusion that is reinforced by the fact that a single theory of stellar structure and evolution suffices for both the Sun and other stars. This alone, however, is probably insufficient to guarantee that the Sun is completely normal in terms of its rotation, its magnetic activity, or the variability that accompanies that activity. Both theory and observation also agree, however, that the history of rotation for solar-type stars is a story of rapidly convergent evolution. We may therefore be fairly confident that the young Sun rotated more rapidly than does the present-day Sun, and that the Sun will continue to slow as it ages. More provocatively, we may assert that a single (or, more generally, a tidally non-interacting) star of the same mass, chemical composition, and age as the Sun will be found to rotate at about the same rate as the Sun, and that its activity and variability will also closely resemble those of the Sun. It is this expectation that valid stellar proxies for the Sun (i.e., sunlike stars) exist that underlies the branch of contemporary astrophysics known as the solar-stellar connection. Furthermore, good proxies for the early Sun should be available among young solar-type stars, and solar-type stars from kinematically old populations and subdwarfs should be reasonable proxies for what the Sun is likely to become as it ages further.

5. VARIABILITY PATTERNS OF SUNLIKE STARS

In 1966, Olin Wilson began to monitor the Ca II H+K emission for about 100 stars using the 100 inch (2.54 m) Hooker Telescope at Mount Wilson Observatory [*Wilson*, 1978]. Wilson's observations have been continued as part of the Mount Wilson HK program, at the 60 inch (1.5 m) telescope between 1977 and 1995 [*Baliunas et al.*, 1995], and at the refurbished Hooker telescope after 1995.

Wilson's goal was "to answer the general question, Does the chromospheric activity of main-sequence stars vary with time, and if so, how?" The observational quantity that Wilson used to measure chromospheric emission is known as the S-index, from which *Noyes et al.* [1984] developed their chromospheric emission ratio, R'_{HK}, defined as the

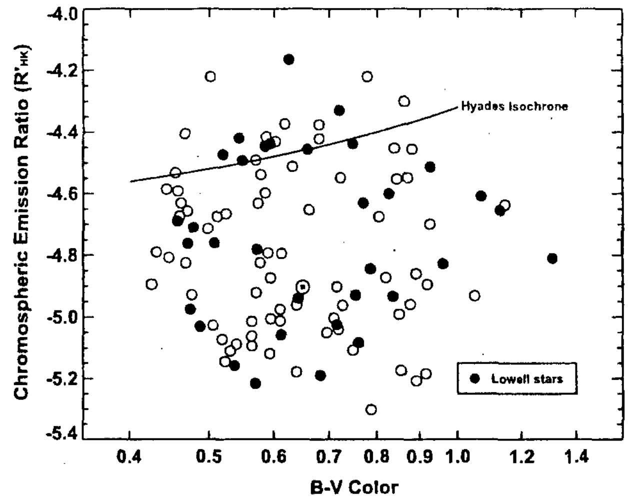


Figure 2. The activity-color plot for the augmented Wilson sample. Activity increases upward, and mass (B-V color is related to mass) decreases rightward. The position of the Sun in the lower left center of the diagram is indicated by its symbol. The Hyades isochrone marks the locus of young stars about 15% the age of the Sun. Filled symbols designate the subset observed photometrically from Lowell Observatory.

chromospheric HK emission of a star normalized by its bolometric luminosity. The conversion to R'_{HK} also corrects for a color effect present in the S-index and removes the photospheric contribution to the line core emission. In Wilson's sample, R'_{HK} ranges (in logarithmic units) from about –4.1 to –5.3; the solar value is –4.94. Figure 2 shows the distribution of Wilson's sample (including a few stars added later to the Mount Wilson HK program) on an activity-color plot.

Wilson did not set out to study only sunlike stars. It is now clear that his sample includes several subgiants: Wilson himself recognized the probability that his sample contained some evolved stars. The release of the Hipparcos parallaxes has now enabled calculation of absolute magnitudes for the stars, independent of their MK spectral classifications. Figure 3 shows the HR diagram for the Wilson sample.

We may quantitatively assess each star of Wilson's sample as a solar analog by measuring its distance from the Sun in the three-dimensional M, B-V, R'_{HK} manifold. For example, if we weight equally distances of 1.0 mag in M_V, 0.1 mag in B-V, and 0.2 in log R'_{HK} (about 0.05 in the S-index), we find that the best solar analog among Wilson's stars is HD 126053 (0.28 units) whose variability, it turns out, does not much resemble that of the Sun [*Baliunas et al.*, 1995; *G. W. Henry*, 2001, private communication]. By the same weighting, the current favorite candidate for solar twin, HD

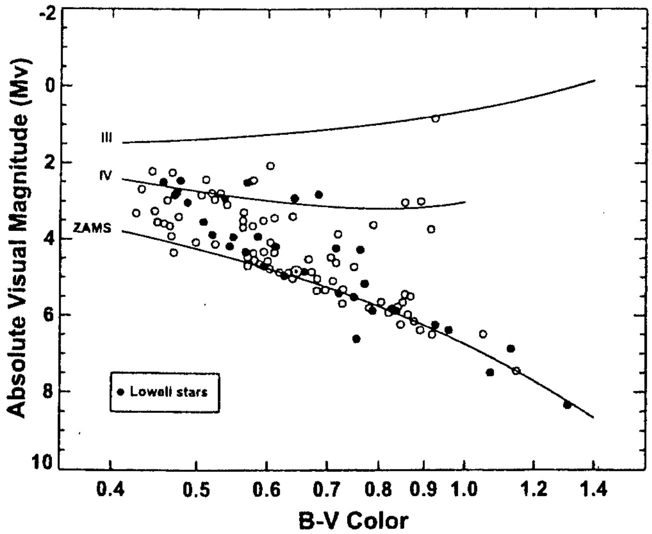


Figure 3. The Hertzsprung-Russell (color-luminosity) diagram for the augmented Wilson sample. The position of the Sun in this diagram is indicated by its symbol. Filled symbols designate the subset observed photometrically from Lowell Observatory.

146233 (18 Sco), is 0.02 units distant. In anticipation, it may also be noted that the closest solar analogs in the Lowell subset of the Wilson stars are HD 143761 (0.96 units) and HD 114710 (1.29 units). It is somewhat disappointing to learn in hindsight that there are no very good solar twins in either Wilson's sample or, especially, the Lowell subset. Despite these limitations, the Wilson stars are the core of our heritage of time-series measurements, and will remain so until results from more narrowly selected samples of stars, now being observed at the Mount Wilson and Fairborn Observatories, become available.

The temporal variation of stellar activity may be classified into three categories [*Baliunas et al.,* 1997], as shown in Figure 4. Young, rapidly rotating stars tend to vary erratically, rather than in a smooth cycle like the Sun. About 80% of older, more slowly rotating stars, including the Sun, tend to show regular activity cycles, and the remaining 20% show little or no variation at all. The inactivity of these latter stars is not necessarily a consequence of great age; the one demonstrably old star in the Wilson sample, the subdwarf shown well below the ZAMS in Figure 3, currently has a relatively vigorous cycle. Rather, these inactive stars may be temporarily in low activity states analogous to the Sun's Maunder Minimum.

Stellar activity cycles, when present, often seem to be about a decade in length. Finding a simple explanation for this fact has become somewhat like the quest for the Holy Grail, and an equally elusive goal [e.g., *Saar and Brandenburg,* 1999]. Among older stars, those more massive than the Sun tend to show low amplitude cycles, whereas those less massive than the Sun often have strong cycles. In fact, stars with strong, "sunlike" cycles (selected subjectively from *Baliunas et al.,* [1995]) tend to occupy a fairly narrow range in an activity-color plot, as shown in Figure 5, with the Sun near the high-mass end of the distribution. Apparently, the Sun has a fairly prominent activity cycle, as traced by its HK emission, for a star of its mass.

The photometric variability of ordinary, lower main-sequence stars was first detected among members of young clusters such as the Pleiades and Hyades. These studies helped inspire a program, begun at Lowell Observatory in 1984, to study the long-term photometric variability of lower main-sequence field stars [*Lockwood et al.,* 1997; *Radick et al.,* 1998]. The Lowell program sampled stars bracketing the Sun in temperature and average activity level. It included 41 program stars, 34 of which were selected from the stars of the Mount Wilson HK program. From these measurements, we now know that the amplitude of the year-to-year photometric variation for young, active stars (including those in young clusters) is typically several percent. It decreases dramatically, typically by a factor of thirty or so, to a level approaching the detection limit of the measurements (about 0.001 mag ≈ 0.1%) among stars similar to the Sun in age and average activity. In contrast, the corresponding decrease in chromospheric Ca HK variation is only about a factor of three. Figures 6 and 7 show representative time series for a young star, probably several hundred Myr old (HD 1835), and an older star, probably comparable to the Sun in age (HD 10476). A catalog of time series plots like the two illustrated may be found in *Radick et al.* [1998]. In addition to the differences in scale, a careful look at the

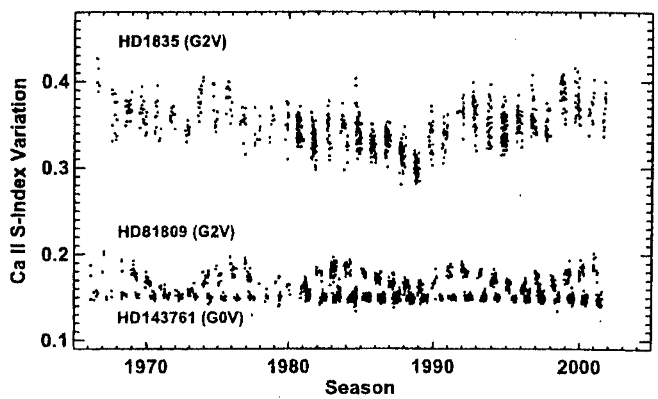


Figure 4. HK time series for three stars (1) HD 1835, a young, active star, (2) HD 81809, an older star with a sunlike activity cycle, and (3) HD 143761, an inactive older star.

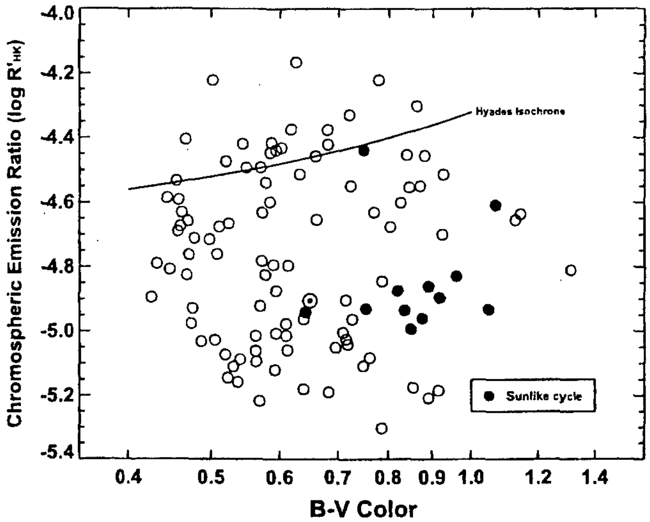


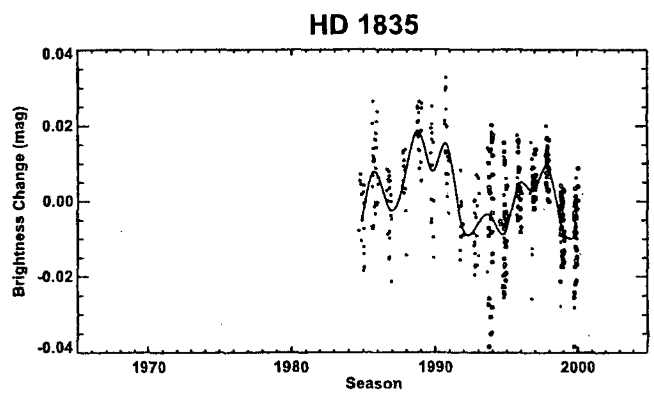
Figure 5. The incidence of pronounced activity cycles among the stars of the Wilson sample. With the possible exception of HD 81809 (a subgiant), the stars with prominent, Sun-like cycles are less massive than the Sun.

time series shown in Figures 6 and 7 reveals another interesting fact: whereas the year-to-year brightness changes of HD 10476 tend to correlate directly with the activity variations shown by Ca HK emission, just as for the Sun, the time series for HD 1835 show anticorrelated variations. In fact, this pattern appears to distinguish young, active stars from older, more sunlike stars in general, as shown in Figure 8.

In 1993, measurements similar to the Lowell program were begun at the Fairborn Observatory. Although detailed comparison of the observations has only begun, it is already clear that these newer observations validate the broad outline of variability among sunlike stars sketched in the preceding paragraph. In general, photometric variation is fairly common across the entire lower main sequence, with about half of the combined sample of several hundred stars showing detectable variability on the year-to-year time scale [*Lockwood et al.*, 1997; *Henry*, 1999].

6. EVIDENCE FOR MAUNDER MINIMA STATES AMONG SUNLIKE STARS

What insight into states of solar activity such as the Maunder Minimum, which have not been observed on the Sun during the modern era, do stellar observations provide? As mentioned above, among older, less active stars like the Sun, about 20% show little or no variability at all. It has been suggested that these stars may currently be in activity states resembling the Maunder Minimum [*Baliunas et al.*, 1997]. The numbers support this suggestion, if the Sun itself spends about 20% of its time in such states. More interesting, however, would be to watch a star making the transition between a cycling state and no variation, or vice-versa. Sufficient stars have been observed long enough that one might expect to find a few cases of this behavior in the presently-available database. In fact, the search turns up no compelling examples: what is found are several stars whose cycle amplitude is clearly changing (generally, decreasing) in a secular fashion. HD 10476, shown in Fig. 7, is a good example of this. It also appears in this case that the photometric brightness amplitude is decreasing along with the HK emission. Whether HD 10476 is actually entering a Maunder Minimum state, however, remains to be determined. On several occasions, the Sun itself has presented us with sequences of several activity cycles that decrease (or increase) regularly in amplitude, without entering a Maunder Minimum state. We may simply have to watch stars like HD 10476 for several more decades before it becomes clear what is happening.



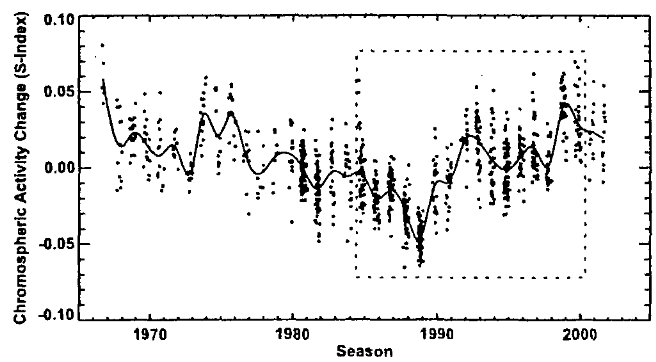


Figure 6. Photometric (top) and chromospheric HK (bottom) time series for HD 1835, a young, active star. The dotted-line box in the lower panel encloses the portion of the Mount Wilson Ca HK emission observations during which photometric measurements were also made at Lowell Observatory.

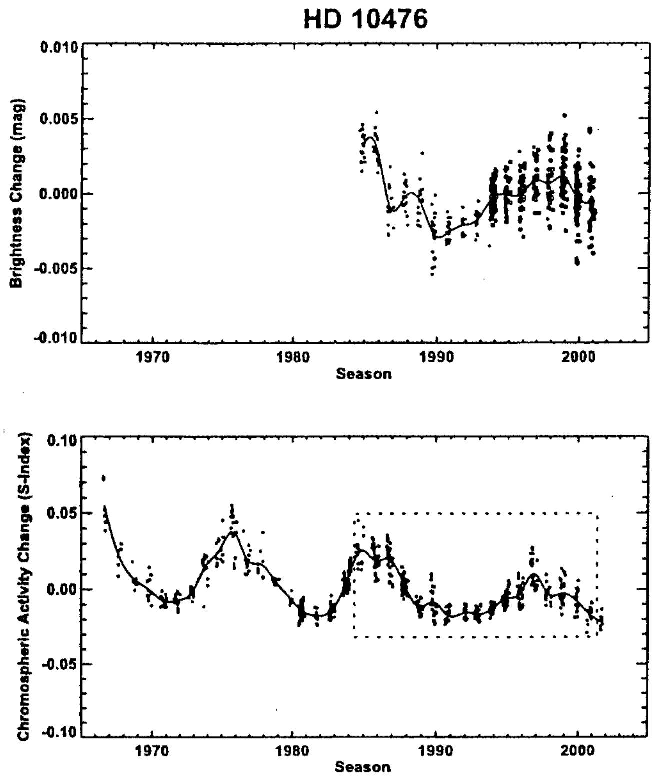


Figure 7. Photometric (top) and chromospheric HK (bottom) time series for HD 10476, an older star with a prominent activity cycle. Note that the scale of the upper panel is 4x that of the corresponding panel of Figure 6, whereas the lower panels have the same scale.

7. THE STELLAR MID-LIFE CRISIS

Twenty years ago, *Vaughan and Preston* [1980] noted a relative lack of F- and G-type stars with intermediate activity (i.e., log $R'_{HK} \sim -4.7$). The suggestion that this "Vaughan-Preston gap" might represent an abrupt change in the nature of stellar chromospheric emission at an age of perhaps 2 Gyr prompted a rebuttal [*Hartmann et al.*, 1984], which argued that the gap is a statistical artifact created by saturation at high levels of emission and a floor at low levels. Since then the Vaughan-Preston gap has lingered, mainly, it seems, as a curiosity. And since then, evidence has continued to grow that something rather dramatic happens to the activity and variability of sunlike stars at an age of about 2 Gyr. Stars younger than this seem rarely to show simple, regular, well-defined activity cycles like that of the Sun. Rather, they vary irregularly, and some appear to vary with at least two comparably-long periodicities operating simultaneously [*Baliunas et al.*, 1995]. There seems to be a real, qualitative difference in the character of variation, recalling the old idea that the highly nonlinear stellar dynamo may operate in more complex and multiple modes as rotation rate increases. There is a second distinction between young and old stars: at an age greater than ~1 Gyr, a sunlike star apparently switches its variability, from a strongly spot dominated mode to a rather different form that is weakly faculae-driven, like the present-day Sun. The transition seems to be abrupt, because we have not found an example of an active sunlike star (as indicated by Ca HK emission, for example) that does not also vary photometrically. In other words, there seems always to be an imbalance between dark and bright features, which suggests that the tendency to create faculae rather than spots does not gradually evolve as a star's rotation slows, but instead appears rather suddenly.

As mentioned earlier, there is opinion that the basic convective pattern of a lower main-sequence star changes as its rotation rate decreases, from elongated rolls aligned parallel to the stellar rotation axis to a cellular pattern more reminiscent of solar granulation. It is tempting to speculate that the Vaughan-Preston gap marks this transition in convective modes, and that this transition affects the operation of the dynamo strongly enough to change the phenomenology of stellar variability.

If there is, indeed, a stellar midlife crisis at an age of about 2 Gyr (and log $R'_{HK} \sim -4.7$), then HD 114710 (see Figure 8) must be near or just through it. The photometric and Ca HK time series for this star, shown in Figure 9, sug-

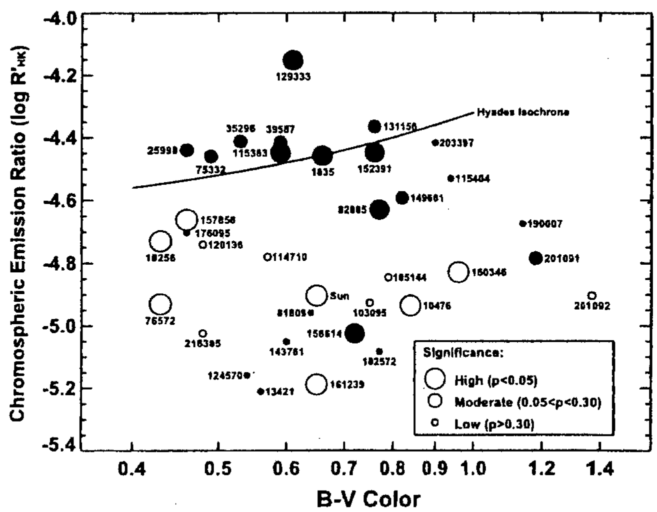


Figure 8. Correlation between year-to-year photometric brightness and Ca HK emission variations, displayed on activity-color axes. The size of each symbol indicates the significance of the correlation. Open symbols are used to represent stars (like the Sun) that become brighter as their HK emission increases. Filled symbols represent anti-correlated behavior.

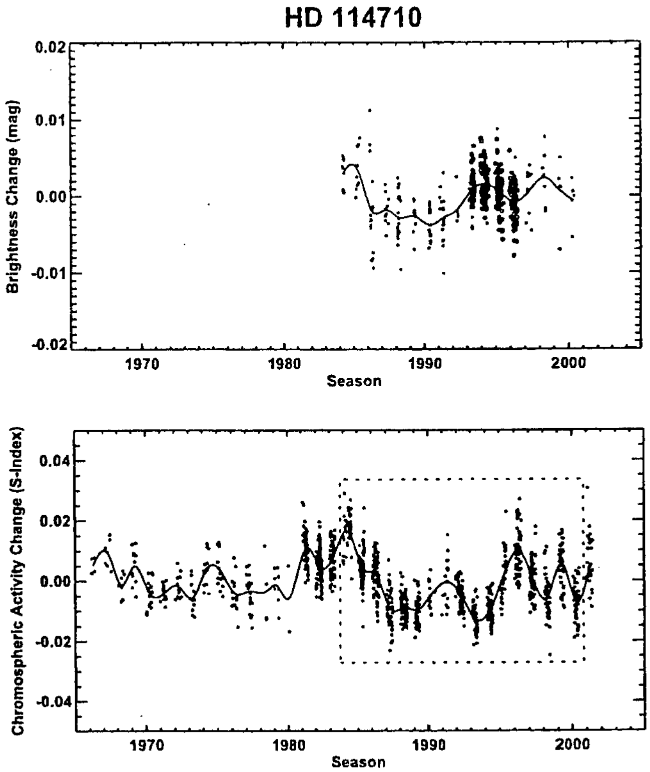


Figure 9. Photometric and Ca HK time series for HD 114710, a star of intermediate age.

gest that it indeed has not yet quite made up its mind about how to behave. According to *Baliunas et al.* [1995], it is a dual-period star, with a 16.6 yr cycle superposed on a 9.6 yr cycle. Its photometric variation, while strong relative to the Sun's, is nevertheless less robust than that of a young star like HD 1835 (Figure 6). Figure 9 also clearly suggests that the photometric brightness and Ca HK emission of HD 114710 vary in step, like the Sun and unlike a young star. (Figure 8, which implies no strong correlation for this particular star, is based on data between 1988 and 1995. Figure 9 indicates that the sense of the correlation is unclear when only that restricted time span is considered.)

8. SUMMARY: THE SUN IN TIME

The story of the activity and variability of a sunlike star on evolutionary time scales is a story of decay. The inexorable decrease in the star's rotation rate as it loses angular momentum through its magnetic wind decrees this fate.

As a young star, the Sun probably resembled HD 1835. Its rotation period slowed, from a few days at an age of 100 Myr to perhaps a week at an age of 700 Myr, and its level of magnetic activity also declined, probably by a comparable factor. Its activity level, nevertheless, remained several times greater than it is today. Its activity varied strongly, but irregularly, on time scales of days to years. The corresponding brightness variations could have been 30–50 times stronger than the Sun's are today. This variability was driven by dark features, probably spots, rather than by bright features as today. Whether these spots were larger or simply more numerous than the spots on the present-day Sun is hard to say. Spot models and Doppler images of extremely active stars (often interacting binaries) tend to imply small numbers of enormous spots, often with one at a rotational pole, reminiscent of the continents on Earth. In a provocative paper, however, *Eaton et al.* [1996] demonstrated that a large number of moderately sized spots, placed randomly in space and time on a differentially rotating star, explain equally well the observed variability of active stars, including the appearance of pseudo-cycles in the time series.

At an age of perhaps 2 Gyr, by the time its rotation had slowed by another factor of two, the Sun apparently realized, perhaps gradually but maybe suddenly, that it was no longer a young star. It began dressing differently—spots were out, faculae were in, at least in preference. Gone also was the intemperance of youth—rather than varying erratically, it now found a dignified, regular cycle more to its taste. Apparently, it also began taking naps, shutting off its cyclic behavior more-or-less completely every few centuries to relax in episodes like the Maunder Minimum. It had become a middle-aged star.

The stars suggest that the Sun's future is likely to resemble its present, at least during the remaining 4 Gyr or so of its main-sequence lifetime. Its rotation will continue to slow, perhaps by another 30%, and its average activity will also decline. It may very well continue its present pattern of activity cycles, interrupted by quiescent episodes. Among sunlike stars, middle age lasts a very long time.

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